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**13. ABSTRACT (Maximum 200 words)**

The behaviour of liquid fuel drops is studied by numerical simulations. The Navier-Stokes equations are solved by a finite difference/front tracking technique that allows resolution of inertial and viscous forces as well as the inclusion of surface tension at the deformable boundary between the fuel and the air. Two- and three-dimensional simulations are used to determine how the lift and the drag depend on the shear rate of the fluid. The deformation of the drops play a major role and while a nearly spherical drop experiences lift in the same direction as a solid particle, relatively modest deformation can lead to a lift force in the opposite direction. To examine more complex problems, a new three-dimensional code has been written that allows local grid refinement and the use of cylindrical coordinates. This code has been used to examine the developemt of three-dimensional disturbances during the primary breakup of jets. At finite amplitude the three-dimensional disturbance can dominate the two-dimensional one and lead to "fiber" breakup.

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# COMPUTATIONS OF DROPLET/FLOW INTERACTIONS IN SPRAYS

## AFOSR-contract F49620-97-1-0525 (AASERT)

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The behavior of liquid fuel drops is studied by numerical simulations. The Navier-Stokes equations are solved by a finite difference/front tracking technique that allows resolution of inertial and viscous forces as well as the inclusion of surface tension at the deformable boundary between the fuel and the air. Two- and three-dimensional simulations are used to determine how the lift and the drag depend on the shear rate of the fluid. The deformation of the drops play a major role and while a nearly spherical drop experiences lift in the same direction as a solid particle, relatively modest deformation can lead to a lift force in the opposite direction. To examine more complex problems, a new three-dimensional code has been written that allows local grid refinement and the use of cylindrical coordinates. This code has been used to examine the development of three-dimensional disturbances during the primary breakup of jets. At finite amplitude the three-dimensional disturbance can dominate the two-dimensional one and lead to "fiber" breakup.

## Objectives

Computational investigations of the motion of drops in sprays are being done. The main part of the study focuses on the lift force of deformable drops and the flow modification due to drops, but droplet/droplet interactions and heat and mass transfer from drops will also be examined. Simulations of the unsteady motion of deformable drops in well defined flow fields will be conducted and the lift and drag of the drops found as a function of the various parameters of the flow. Of particular interest is a quantification of the magnitude of the lift and its sign, as a function of the deformability of the drop. The motion of drops in more complex unsteady fields, such as shear layers, will also be examined and the flow modification by the drops quantified. The effect of the relative size of the effective length scales of the flow and the drop size will be examined and whether the drops enhance or decrease the velocity fluctuation in the flow. In addition to understanding the flow modifications, the study will identify under what conditions the modification of the flow field is important and whether these modifications can be accounted for by a simple model in engineering computations of sprays. The heat and mass transfer from drops will also be investigated and the transfer coefficients needed for engineering models computed.

These computations are made possible by a recently developed numerical technique that has been used already for a number of multifluid problems. The method incorporates an explicit tracking of the drop surface with a finite difference method for the full Navier-Stokes equations for the drop and the ambient gas. Arbitrary differences in density and viscosity are possible, large surface deformations are allowed, and surface tension is fully accounted for. For problems with mass and heat transfer, conservation equations for mass and energy are solved also. Recent implementation of this method into a fully parallel three-dimensional code will allow large-scale simulations that include a wide range of scales.

## Status of Effort:

Several three-dimensional simulations of drops in shear flows have been done. For bubbles it has been shown that deformation have a major influence on the lift force, including changing its sign for relatively modest deformation. The simulations, as well as a number of two-dimensional ones, done to establish the necessary resolution, have shown that this is true for drops as well—as expected. We are currently examining the effects of the various parameters, including those imposed by the numerical setup, and trying to parameterize the lift force so that it can be used in simulations using point particles.

A three-dimensional code designed to allow us to look at a "pie-slice" of a nearly axisymmetric flows and refine the grid in regions of interest has recently been completed. While the code is still being refined and tested, it has been used for preliminary simulations of the breakup of jets.

## Accomplishments/New Findings:

Simulations of drops in shear flow have shown that deformation have a major impact of the magnitude of the lift force. A spherical drop moving relative to the fluid experiences a lift in the same direction as a solid sphere. If the drop deforms, however, the direction can change. Figure 1 shows a three-dimensional drop in a linear shear. The drop surface and the flow field in a plane cutting through the center of the drop is shown. The drop is moving downward and remains nearly spherical for the particular parameter values used here. The lift force therefore moves it toward the upward moving fluid. In figure 2, two, two-dimensional simulations of a nearly spherical and a deformable drop are shown. The

streamlines in a frame of reference moving with the drops are shown. The shear is indicated on the top of each frame and the velocity of the drop is shown with a bold arrow. As for the three-dimensional drop, the spherical one moves toward larger slip velocity, while the deformed one moves in the other direction. The difference can be explained by examining the circulation around the drops and the flow modification induced by deformation.

Two-dimensional simulations of the breakup of a planar interface have showed that surface tension suppresses the rollup seen for a shear boundary between miscible fluids of similar density and leads to fingers of interpenetrating fluids. For small density differences the evolution is symmetric with respect to the light and the heavy fluid, but for larger density ratios the fold consisting of a heavy fluid becomes smaller and at later time the evolution becomes similar to a breaking wave with heavy fluid being stripped from the crest. Even in two-dimensions the folds can break up into drops. Three-dimensional simulations show that the "folds" are unstable in two ways. If the evolution is essentially two-dimensional, then fluid cylinders perpendicular to the shear are generated and drops are formed when these cylinders breakup by a Rayleigh Instability. If three-dimensional disturbances are strong, the initial "folds" develop into long fingers parallel to the shear and drops are formed by "end-pinch" instability of these fingers. Similar fingers are seen in the "fiber" breakup modes of jets. This evolution has also been seen recently in numerical studies by other investigators. Figure 3 show the "fiber" breakup of a jet. The jet surface is shown at three times along with the outlines of the "pie" shaped computational domain. In the top figure a two-dimensional disturbance has grown to a large amplitude and the three-dimensional instability is just becoming visible. In the middle frame the three-dimensional disturbance has evolved into a long "finger" or "fiber" of the jet fluid penetrating into the ambient fluid. In the bottom frame the finger is breaking up into drops.

During the next year, the focus of the investigation will be three fold:

- The motion of drops and their interaction with the flow, including quantification of the dependency of lift on drop deformation.
- The new three-dimensional code will be completed and tested.
- Investigation of heat and mass transfer will be initiated

**Personnel Supported:**

Warren Tauber, Graduate Student

**Publications (both AASERT and Parent Award):**

G. Tryggvason & S.O. Unverdi. The Shear Breakup of an Immiscible Fluid Interface. Proceedings of the C.S. Yih Memorial Symposium. Ed. W. Shyy. Cambridge University Press, 1999.

G. Tryggvason, A. Esmaeeli, S. Mortazavi, J. Han, and S. Homma. Computations of Multiphase Flows by a Finite Difference/Front Tracking Method. II Applications. In: 29th Computational Fluid Dynamics. Lecture Series 1998-03. Von Karman Institute for Fluid Dynamics.

J. Han. *Numerical Studies of Drop Motion in Axisymmetric Geometry.* Ph. D. Dissertation. University of Michigan, 1998.

W. Tauber, S. O. Unverdi, and G, Tryggvason. The shear breakup of fluid interfaces. Proceedings of the ASME Summer Meeting of the Fluids Division, Washington DC, 1998.

G. Tryggvason, B. Bunner, A. Esmaeeli, and S. Mortazavi. Direct simulations of dispersed flow. Proceedings of the Third International Conference on Multiphase Flow. Lyon, France, June 8-12, 1998.

Journal articles are in preparation

**Interactions/Transitions (both AASERT and Parent Award):**

(a) Since September 1, last year, I have discussed various aspects of the present work in the following presentations:

G. Tryggvason. Seminar at UCSB, Chemical Engineering. 11/21/97

G. Tryggvason. Seminar at the University of Arizona, 1/29/98

G. Tryggvason. Seminar at NASA Lewis Research Center, 3/10/98

J. Han & G. Tryggvason. Air induced breakup of drops. 50th Meeting of the American Physical Society, Div of Fluid Dynamics, Nov. 23-24. San Francisco, CA. Abstracts in Bull. Amer. Phys. Soc

G. Tryggvason, B. Bunner, S. Mortazavi, & A. Esmaeeli "Direct Numerical Simulations of Dispersed Multiphase Flows. 11th Japanese Symposium on CFD. Tokyo, Japan. December, 1997. Invited Opening Lecture. (See also publications)

G. Tryggvason. Computations of Multiphase Flows by a Finite Difference/Front Tracking Method. Lecture Series 1998-03. Von Karman Institute for Fluid Dynamics. Belgium. February 23-27, 1998. (See also publications)

G. Tryggvason, B. Bunner, A. Esmaeeli, and S. Mortazavi. Direct simulations of dispersed flow. Third International Conference on Multiphase Flow. Lyon, France, June 8-12, 1998. (See also publications)

W. Tauber, S. O. Unverdi, and G, Tryggvason. The shear breakup of fluid interfaces. ASME Summer Meeting of the Fluids Division, Washington DC, 1998. (See also publications)

G. Tryggvason & S.O. Unverdi. The Shear Breakup of an Immiscible Fluid Interface. 13th U.S. National Congress of Applied Mechanics. Gainesville, FL, June 21-26, 1998. (See also publications)

(b) I consult regularly for Ford Motor Company, GRI, and the Fermi II Nuclear Power Plant.

(c) The numerical method used in this investigation is currently being used by Dr. E. Steinthorsson at Parker Hannifin Corporation to investigate the formation of a fluid sheet from a SIMPLEX nozzle and the subsequent breakup of the sheet into drops.

**New discoveries, inventions or patents:**

None

**Honors/Awards:**

Invited to give the opening lecture for the 11 Japanese Symposium on CFD. Tokyo, Japan. December, 1997.

Invited to give a series of three lectures at the von Karman Institute

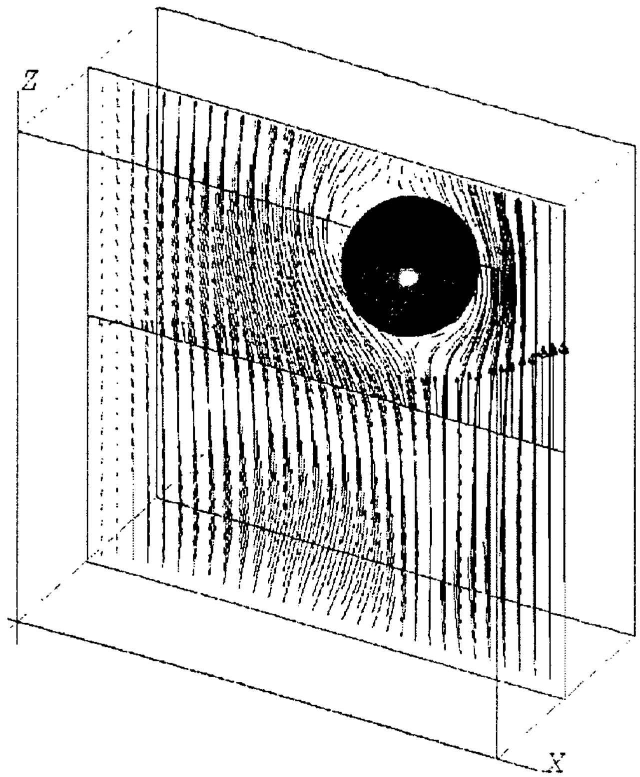


Figure 1. Three-dimensional drop in a linear shear flow. The drop is moving downward remains nearly spherical. The lift force moves it toward the upward moving fluid.

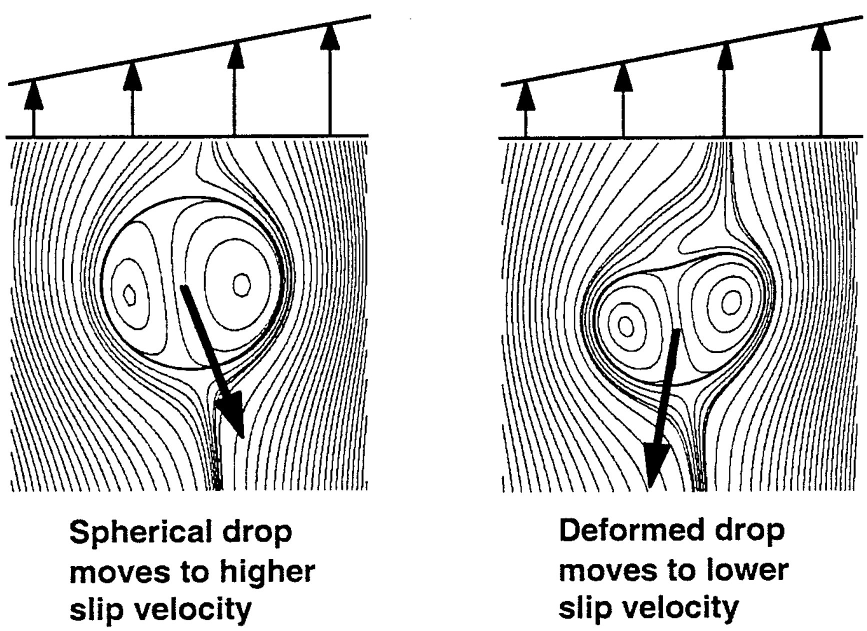


Figure 2. Two-dimensional simulations of a nearly spherical and a deformable drop. The streamlines in a frame of reference moving with the drops are shown.

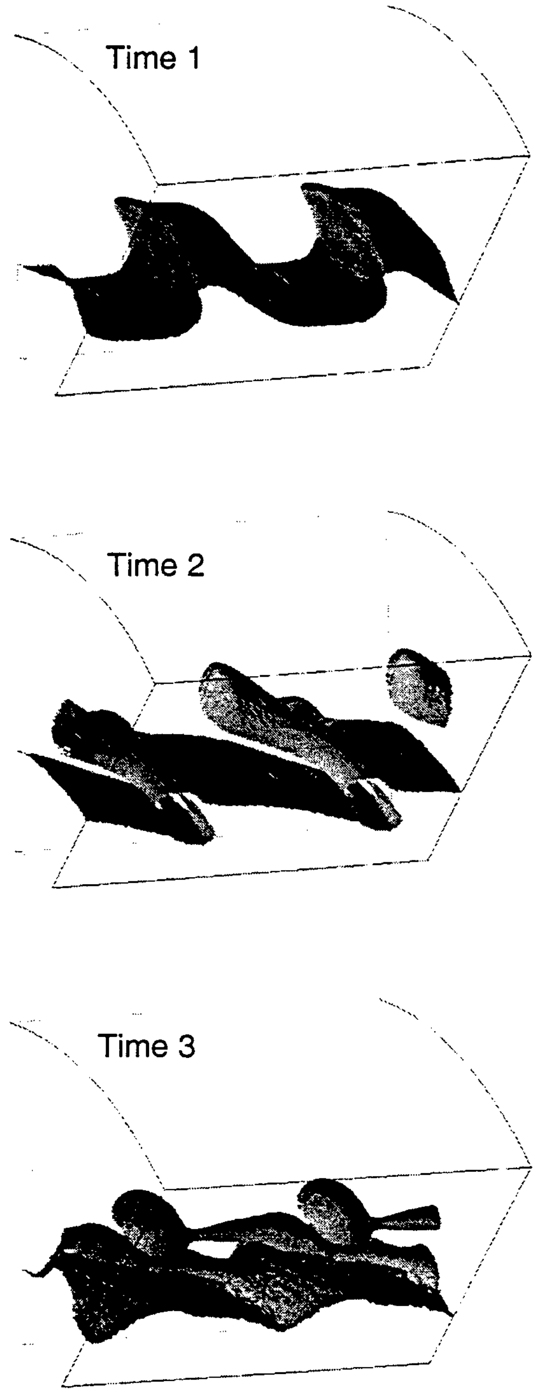


Figure 3. Preliminary simulations of the three-dimensional breakup of a jet. A computational domain in the shape of a "pie" allows the simulations of only a portion of the jet.

**AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT)**
**REPORTING FORM**

The Department of Defense (DoD) requires certain information to evaluate the effectiveness of the AASERT Program. By accepting this Grant which bestows the AASERT funds, the Grantee agrees to provide 1) a brief (not to exceed one page) narrative technical report of the research training activities of the AASERT-funded student(s) and 2) the information requested below. This information should be provided to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1 Grantee identification data: (R&T and Grant numbers found on Page 1 of Grant)

a University of Michigan
University Name

b F49620-97-0525
Grant Number

c. 3484-WS
R&T Number

d Tryggvason, Gretar
P I Name

e. From: 8/31/97 To: 9/1/98
AASERT Reporting Period

NOTE Grant to which AASERT award is attached is referred to hereafter as "Parent Agreement".

2 Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

a Funding $ 97,251

b Number FTEGS 1

3 Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month reporting period

a Funding $ 78,074

b Number FTEGS 1

4 Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period

a Funding $ 39,234

b Number FTEGS 1

c Number UGS 0

VERIFICATION STATEMENT I hereby verify that all students supported by the AASERT award are U.S citizens

Principal Investigator

8/31/98
Date